Do we understand the Initial Stages?

Raju Venugopalan

BNL

IS 2017 Krakow, September 18-22, 2017

No…

…**because the physics of initial stages in hadron-hadron collisions is nonperturbative for most quantities, and nonperturbative QCD is complicated**…

PHYSICAL REVIEW VOLUME 96, NUMBER 1 OCTOBER 1, 1954

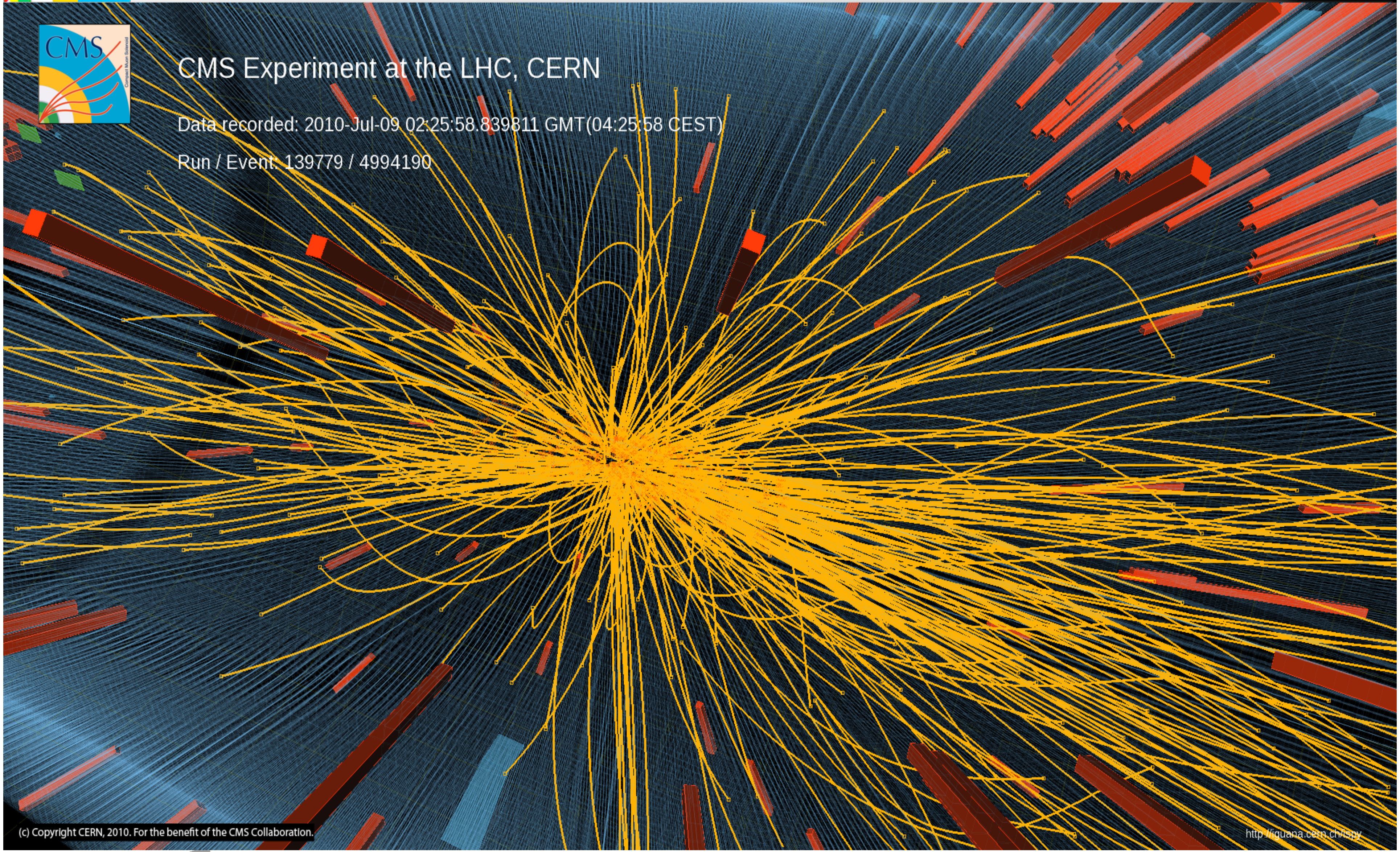
Conservation of Isotopic Spin and Isotopic Gauge Invariance*

C. N. YANG † AND R. L. MILLS
Brookhaven National Laboratory, Upton, New York
(Received June 28, 1954)

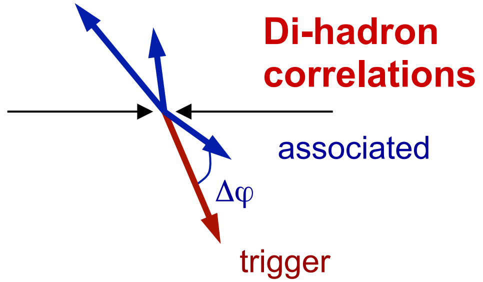
… but very interesting, because it teaches us about
strongly correlated real-time dynamics of a non-Abelian gauge theory

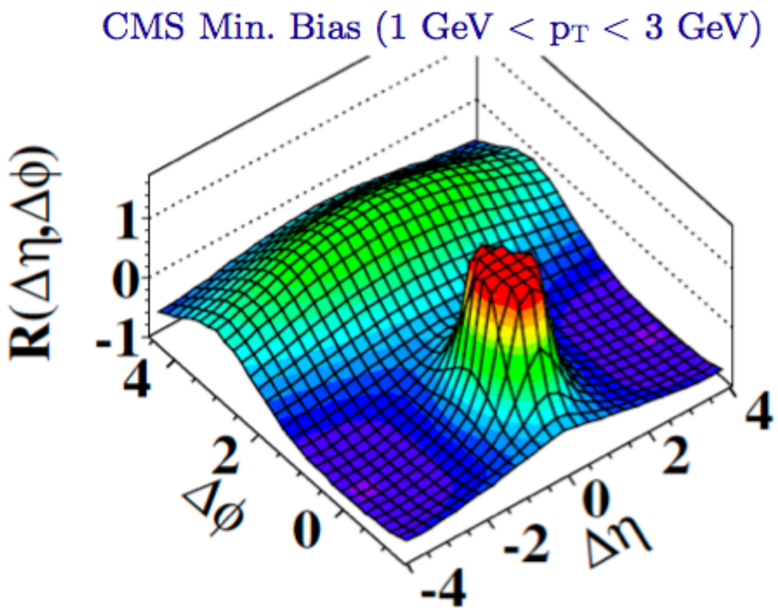
Caveat: This talk is NOT a summary but my limited personal perspective on some recent developments

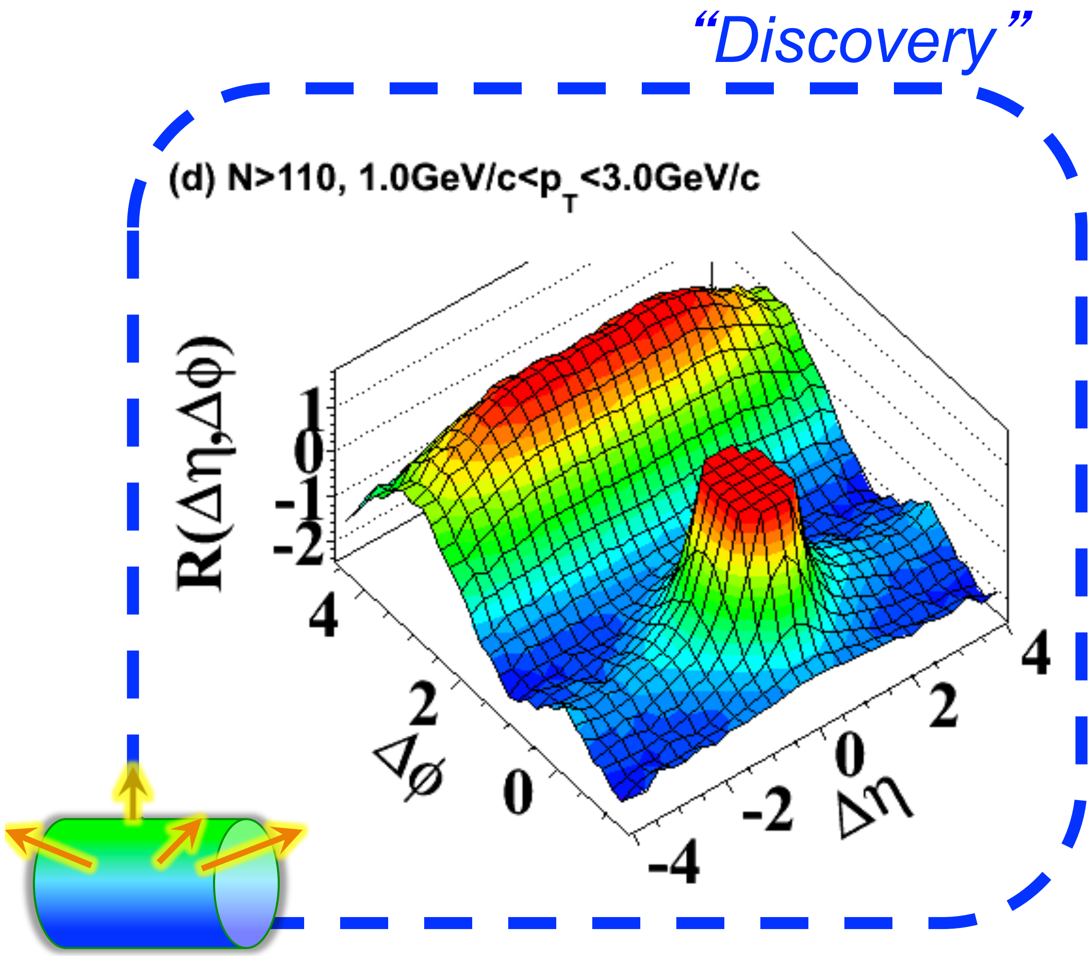
High Multiplicity pp collisions



Two particle correlations: CMS results





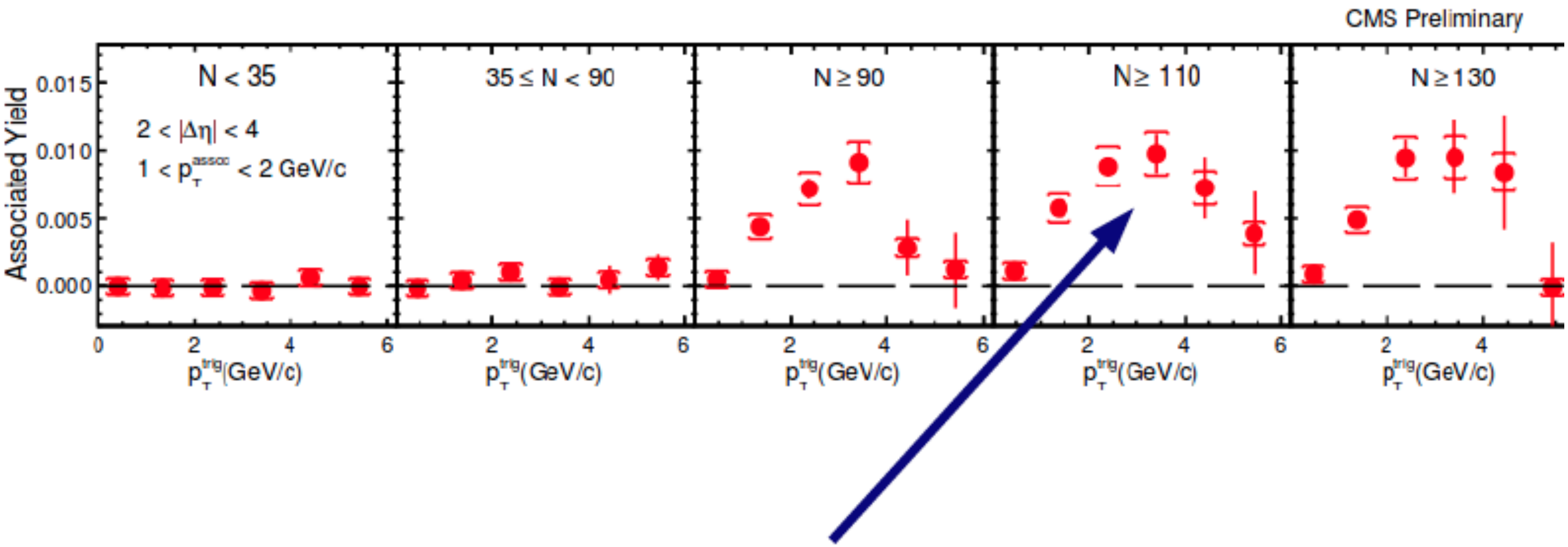


Observation of Long-Range Near-Side Angular Correlations in Proton-Proton Collisions at the LHC CMS Collaboration (Vardan Khachatryan (Yerevan Phys. Inst.) *et al.).* **JHEP 1009 (2010) 091**

Cited by 597 records

5^{th} most cited CMS physics paper to date!

My initial interest (in 2010) was piqued by the sub-structure of the ridge shown:

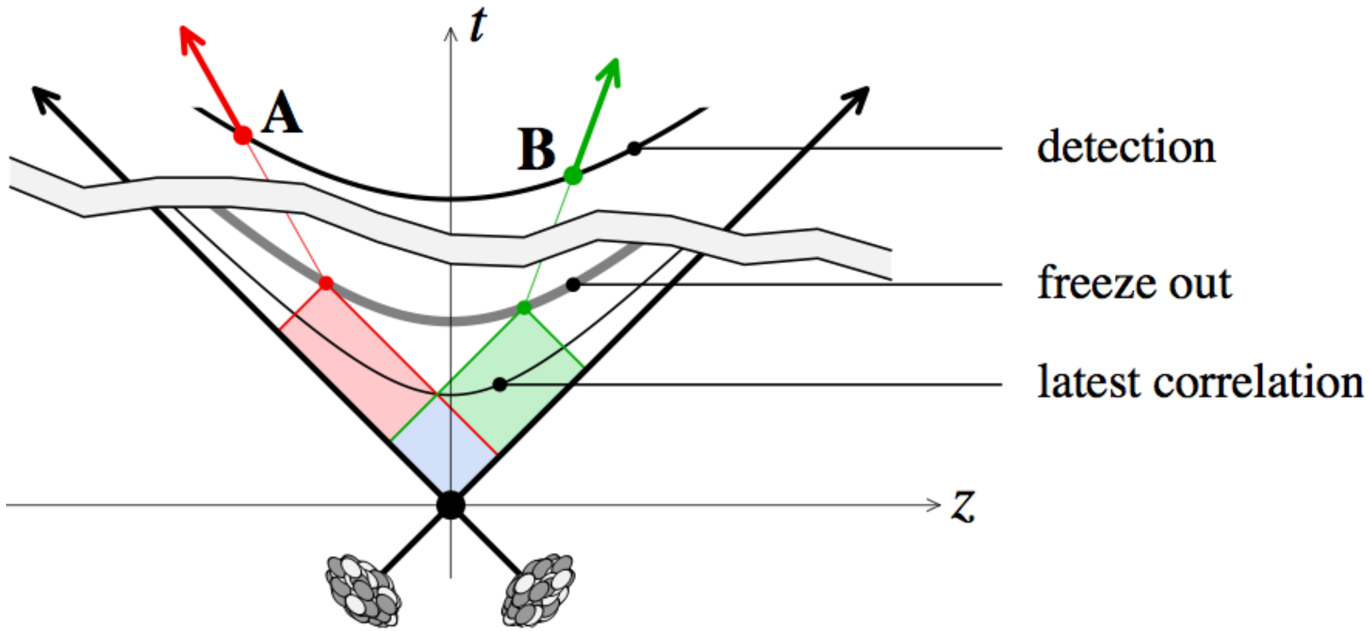


Evidence of a semi-hard scale in the data?

If this scale is ≈ Q_S, since $\alpha_S(Q_S^2) << 1$
could examine this nonperturbative strongly correlated phenomenon in weak coupling

will return to this point later…

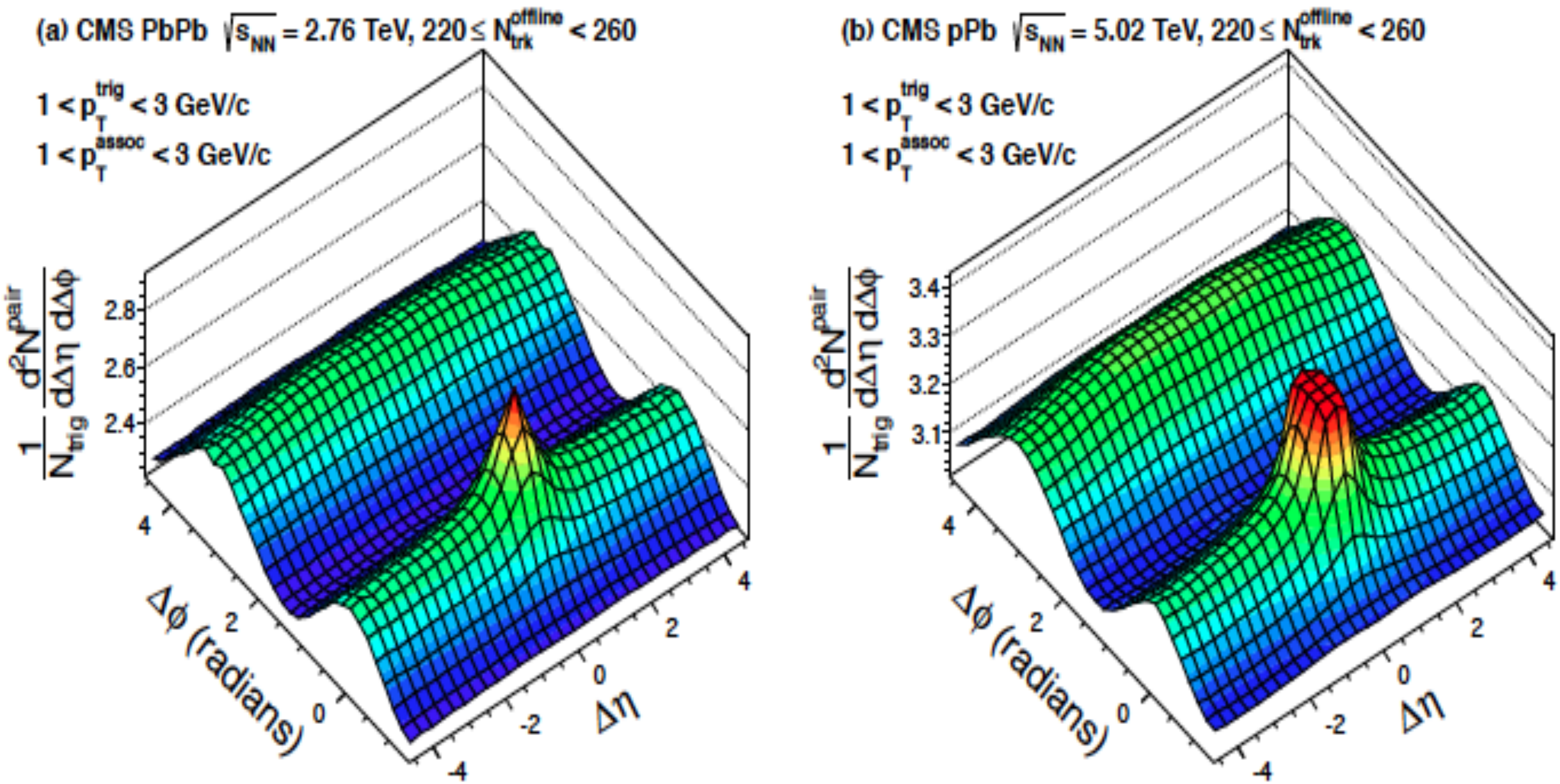
Long range rapidity correlations are a chronometer



$$\tau \leq \tau_{\text{frz-out}} \exp\left(-\frac{1}{2}|y_A - y_B|\right)$$

Long range correlations sensitive to very early time
(fractions of a femtometer ~ 10^{-24} seconds) dynamics in collisions

Another surprise: central p+A looks like peripheral A+A



p+A ridge seen --much large than p+p at same multiplicity and nearly as large as that in peripheral Pb+Pb collisions

First indication that hydrodynamics may play a role in such events

Several early papers by Bozek and Broniowski

See Inside

Particles That Flock: Strange Synchronization Behavior at the Large Hadron Collider

Scientific American, February (2011)

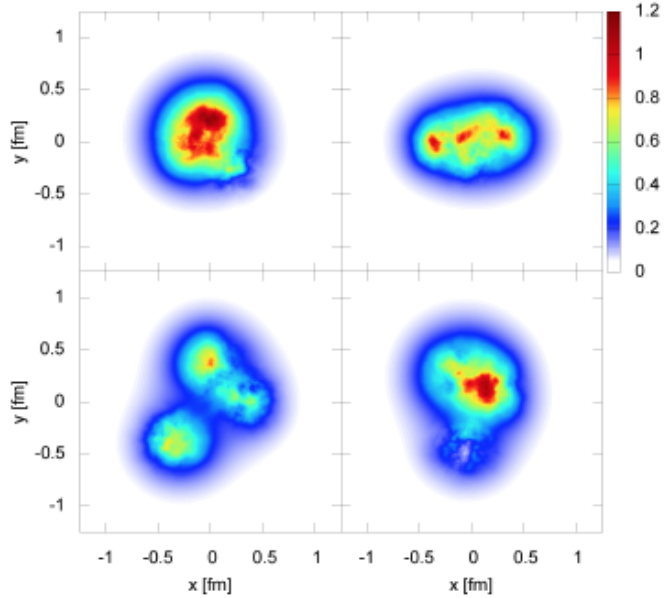
Scientists at the Large Hadron Collider are trying to solve a puzzle of their own making: why particles sometimes fly in sync

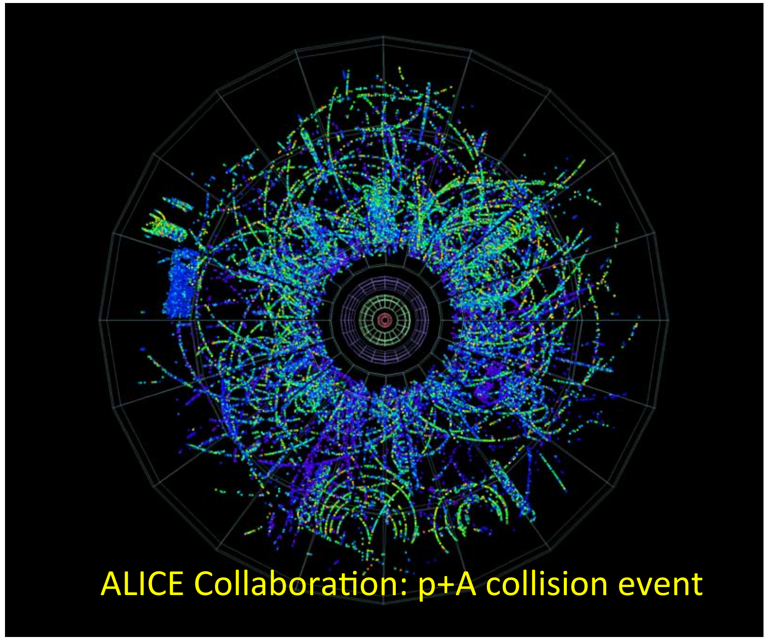
The high-energy collisions of protons in the LHC may be uncovering "a new deep internal structure of the initial protons," says Frank Wilczek of the Massachusetts Institute of Technology, winner of a Nobel Prize

"At these higher energies [of the LHC], one is taking a snapshot of the proton with higher spatial and time resolution than ever before"

Deep internal structure of the proton…
A piece of initial state physics that may matter for the final state

Eccentric protons





Bjorken, Brodsky, Goldhaber, PLB726 (2013) 344

HERA data on incoherent diffractive vector meson production favor this

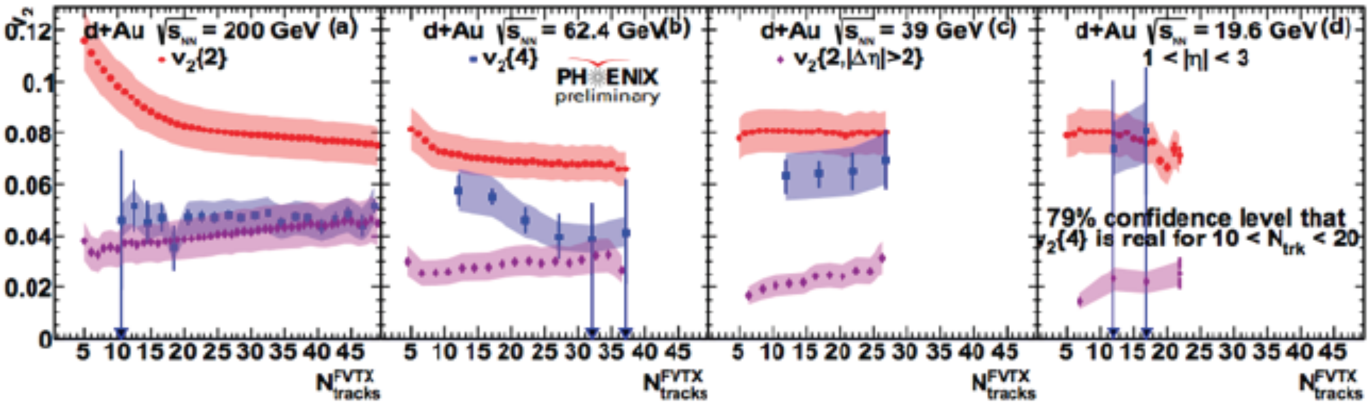
Talks by Schenke and Mantysaari

Timeline of our (mis?) understanding…

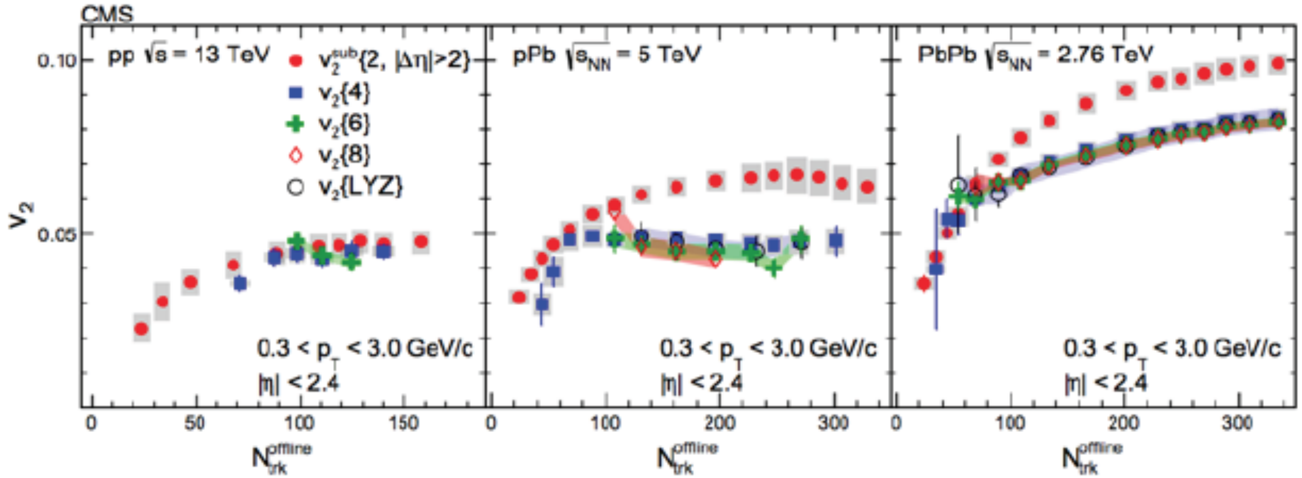
- 2010—Ridge in high multiplicity p+p (LHC)! Probably CGC!
- Early 2010s—QGP in p+Pb!
- Early 2010s—QGP in d+Au!
- Mid 2010s and now-ish—QGP in high multiplicity p+p? QGP in mid-multiplicity p+p?? QGP in d+Au even at low energies???

From Ron Belmont's talk

Collectivity in the sense of $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ is now ubiquitous
…widely believed when first seen to be “proof” of final state response to initial state geometry



R. Belmont PHENIX arXiv:1704.04570



CMS PRL 115 (2015) 012301

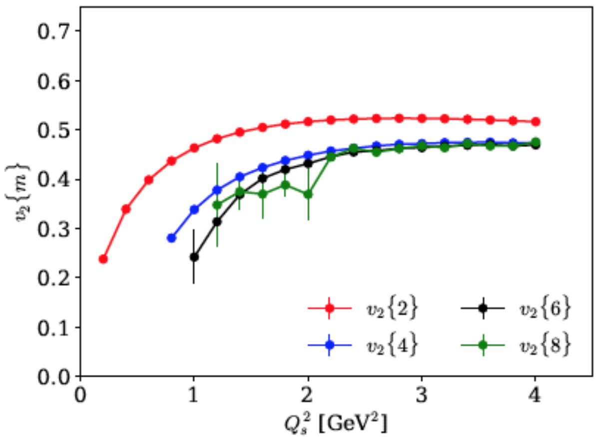
Our understanding of cumulant measurements now more nuanced…

- Multi-particle long-range correlation, i.e. collectivity, could produce $c_2\{4\}$, $c_2\{6\}$.. with any sign: it is the property of the shape of $p(v_2)$
  - Also possible in final state, most models has $p(\varepsilon)$ that give $\varepsilon_n\{2k\}$ with "correct" sign. But the initial geometry in small systems is not settled

➔ sign-change is possible if $c_2\{4\}=\langle v_2^4\rangle-2\langle v_2^2\rangle^2 \propto \langle \varepsilon^4\rangle-2\langle \varepsilon^2\rangle^2>0$ **From talk by Jia**

➔ or $p(\varepsilon)$ may be engineered such that the signs of $\varepsilon_n\{2k\}$ flip

Especially relevant to understanding whether positive $c_2\{4\}$ seen in p+A at RHIC is consistent with flow



Convergence of higher moments also seen in a very simple initial state "color domain" model

Talk by Mace
See also, talk by Kovner

$v_2\{4\}$ also seen from MPI model of initial state QCD interference contributions

Talk by Wiedemann

Our understanding of initial/final state correlations is also more nuanced…

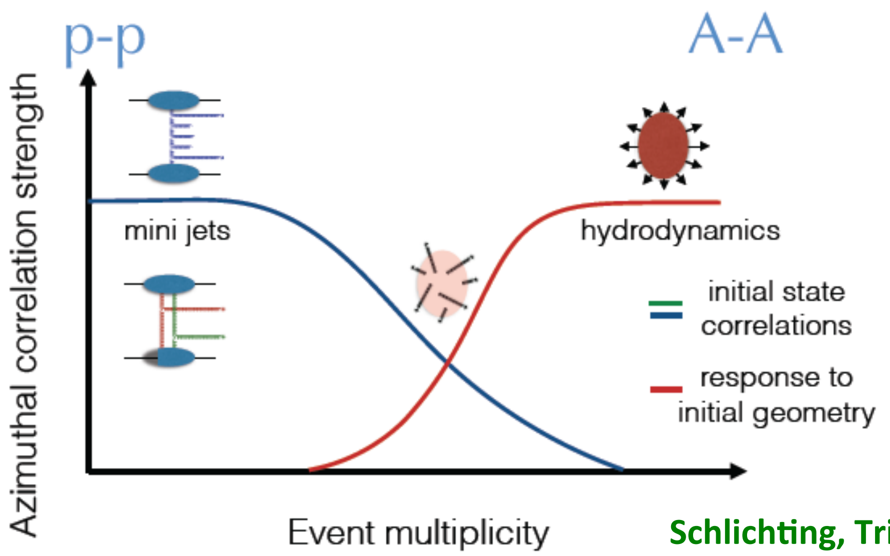
Collectivity: possible origin

Final state		Initial state
• Driven by initial state geometric correlations	~~vs~~	• Driven by initial momentum correlations
• Develops gradually during (hydro) evolution	**and**	• Pre-exist before collisions or develops very soon after
• Requires large multiplicities to facilitate final state interaction		• High-multiplicities are not required, but allowed
• Requires non-trivial initial state geometry (proton shape fluctuations)		• Momentum correlations are present (suppressed by $1/N_c^2$) for "round" p

Talk by Skokov

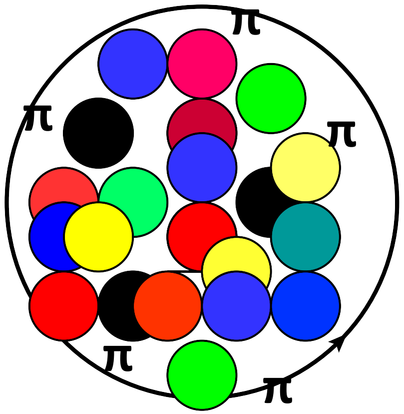
Stated more bluntly…

Saturated wavefunctions in hadron-hadron collisions will generate both non-flow and flow contributions



Schlichting, Tribedy, arXiv:1611.00329

Their relative contributions depend on Q_S, p_T, multiplicity and system size



Saturated gluons have the maximal occupancy possible in QCD ~ $1/\alpha_S$

-- no quasi-particle description possible
at early times for modes with $p_T < Q_S$

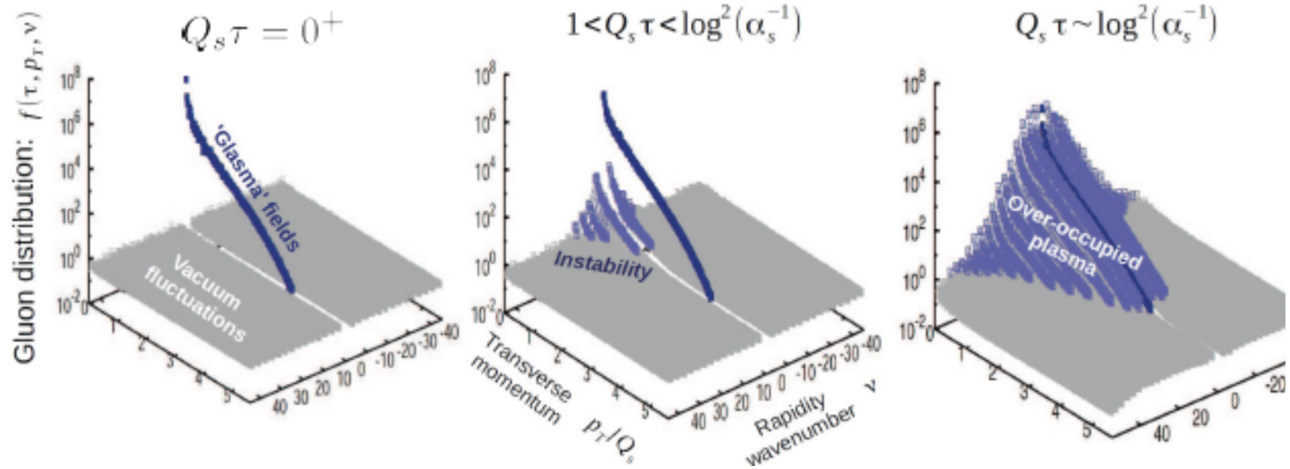
The spacetime evolution of these modes described
by solving the equations of classical QCD:
the Yang-Mills equations
QCD coupling drops out for these modes

Talks by Boguslavski, Fries, Gelis,
Mueller[2], Schenke

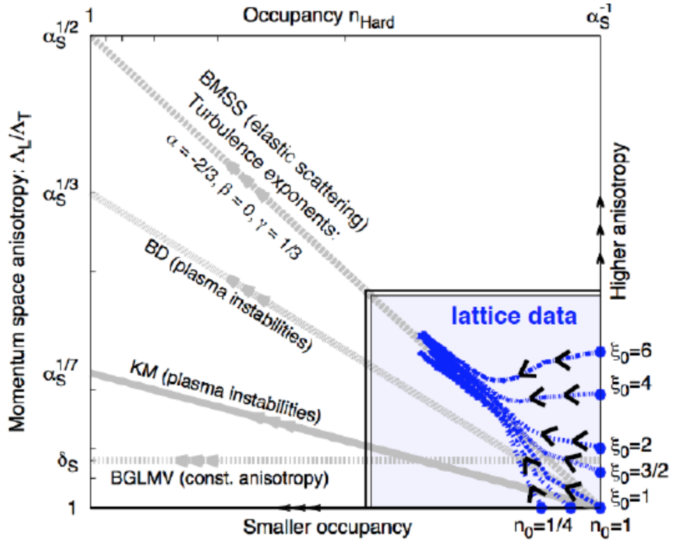
Modes with $p_T >> Q_S$:
Have quasi-particle description, and match
to pQCD … matching can be done order by order in pQCD – jet physics

Flow component at $\tau \approx 1/Q_S$ described by $p_T < Q_S$
Non flow component by $p_T > Q_S$

Subsequent spacetime evolution of "flow component" for $\tau >> 1/Q_S$



Plasma instabilities cause the system to become overoccupied in p_T and p_z very quickly… and system flows to an attractor, which is that of the bottom-up kinetic scenario



Talk by Boguslavski

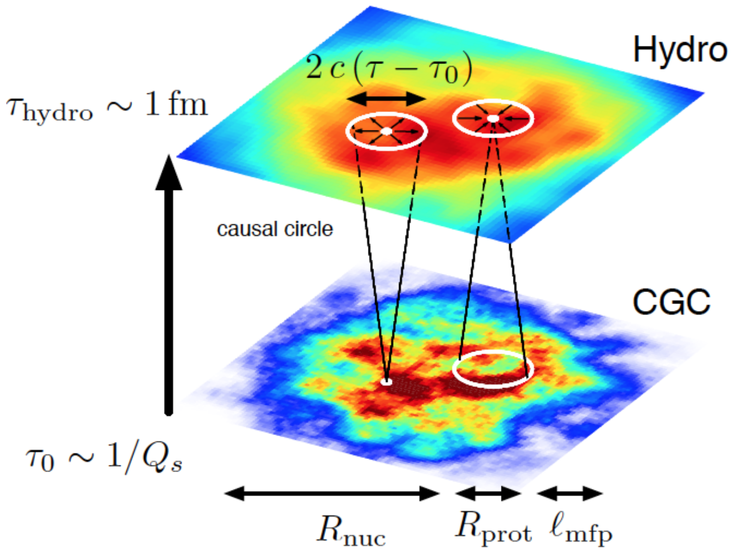
Many open questions and caveats regarding the role of so-called "quantum ½" contributions

Discussed in talks by Gelis and Wu

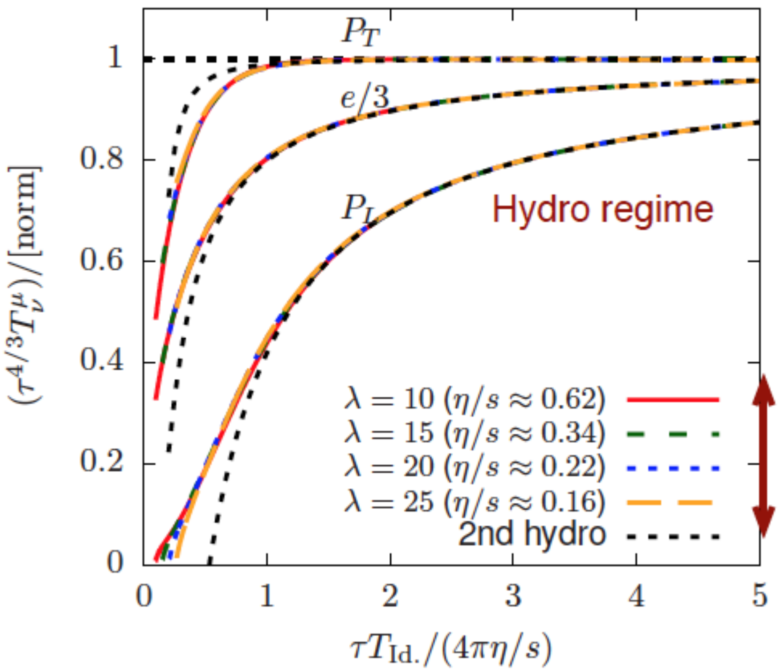
Recent developments in
bottom-up thermalization…

Lumpy "hot spot" transverse structure in IP-Glasma/EKRT survives until matching with hydro

Mapping the CGC fluctuating initial conditions to hydro



When does the background stress tensor approach second order hydrodynamics?



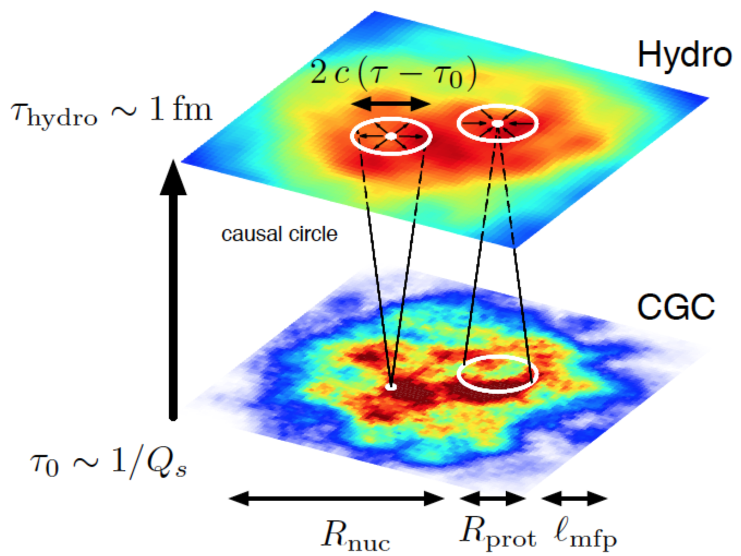
Different values of coupling give different η/s

In terms of eta/s, all couplings thermalize at same scaled time
Keegan, Kurkela, Romatschke, Schee, Zhu

Gives a basis for interpolating from weak coupling results to stronger coupling

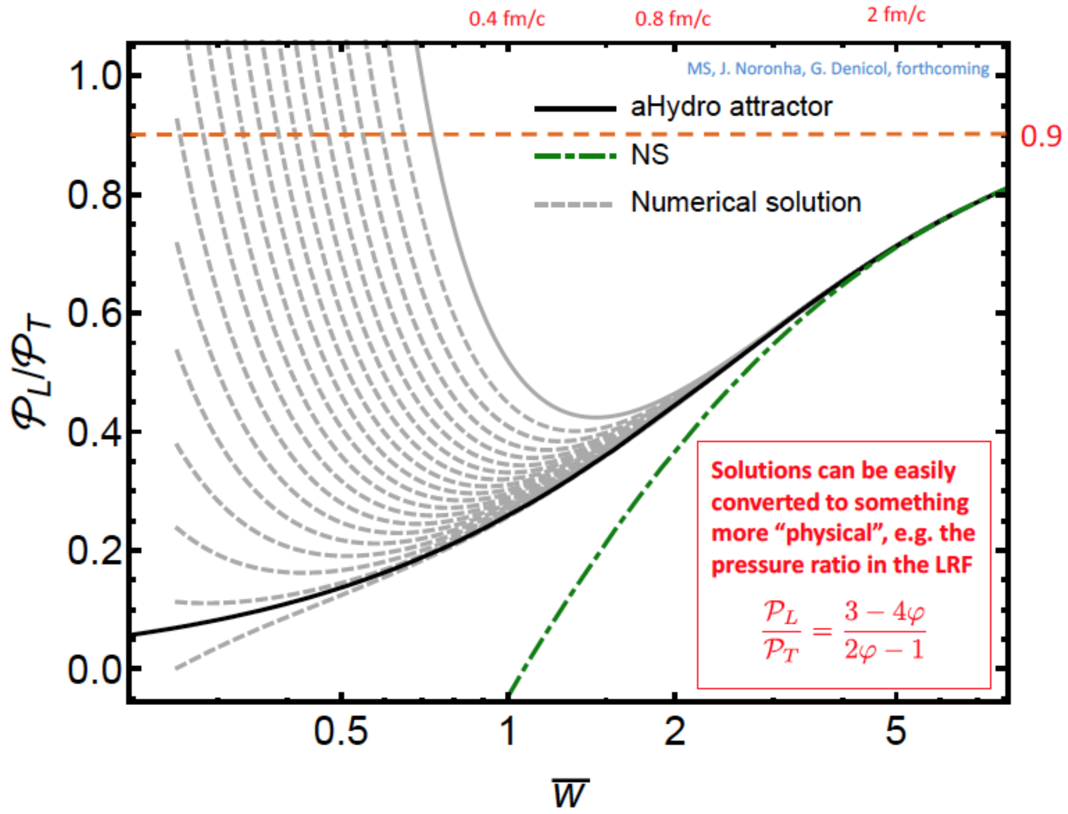
Talks by Teaney and Mazeliauskas

Recent developments in
bottom-up thermalization…



Lumpy "hot spot" transverse structure in IP-Glasma/EKRT survives until matching with hydro

The attractor concept – 0+1d



Talk by Strickland

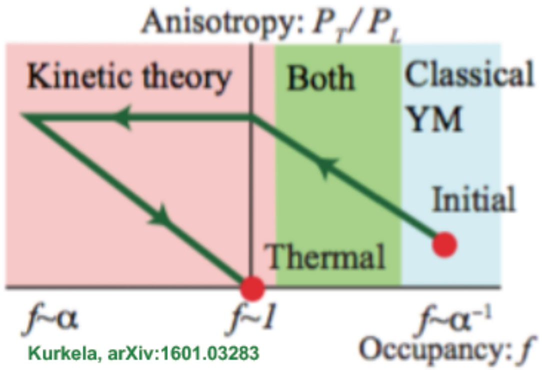
Can one realize the "aHydro Attractor" in the bottom-up framework?

What about “non-flow” mini-jets and jets at the scale $p_T \geq Q_S$?

Fluid dynamics ⇔ final state interactions ⇔ Jet quenching

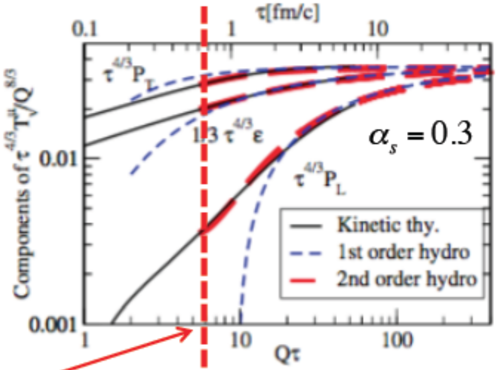
- Bottom-up thermalization formalizes relation between fluid dynamics and jet quenching

R.Baier, A.H. Mueller, D. Schiff, D.T. Son, 2001



Kurkela, arXiv:1601.03283

Kurkela&Zhu, PRL115 (2015)182301



Partonic distributions f(p) governed by **Boltzmann equation.**
We know:

$$\partial_t f(p,t) = -C_{2\leftrightarrow 2}[f] - C_{1\leftrightarrow 2}[f]$$

- f(p) hydrodynamizes on sub-fermi time scale
- “Hydro” & “jet quenching” arise from the same collision kernels

Berges, Eppelbaum, Kurkela, Moore, Schlichting, Venugopalan, …

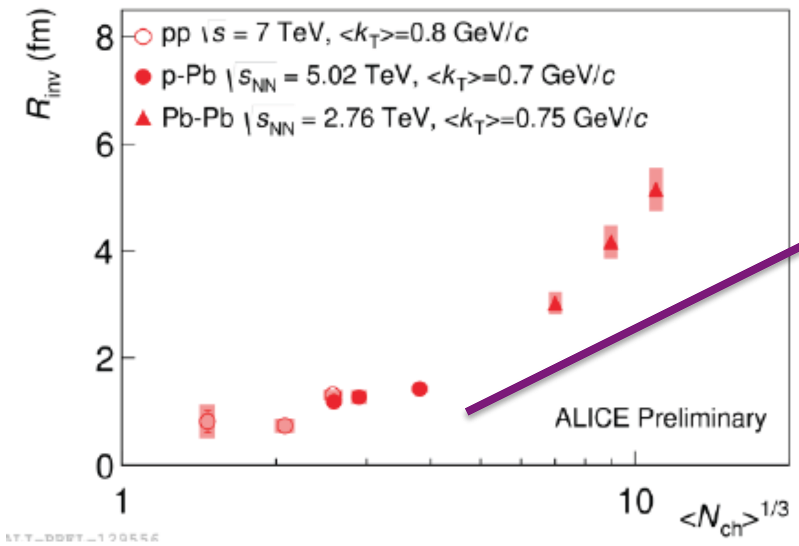
2->2 collision kernel

LPM splitting kernel

Jet quenching and fluid dynamics = two manifestations of the same physics

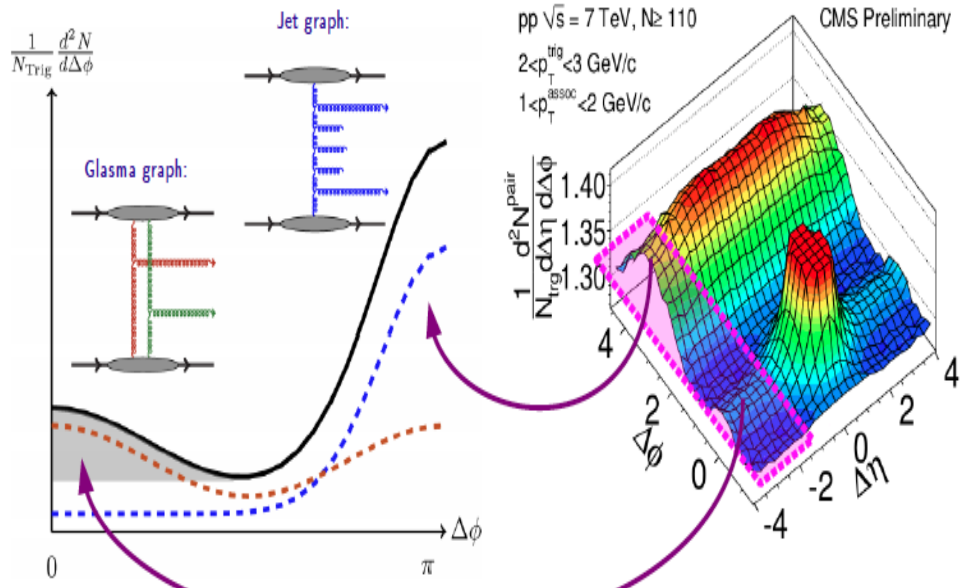
Slide from Wiedemann’s talk

What about this flow+non-flow framework for the smaller systems?



Talk by Zhou

HBT radii indicate that lifetimes of the smaller systems is quite short …little time for rescattering



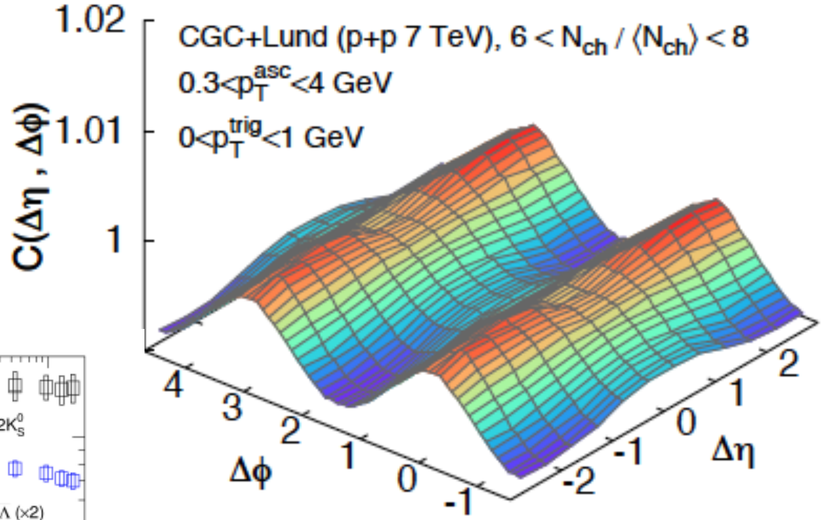
Dusling,RV

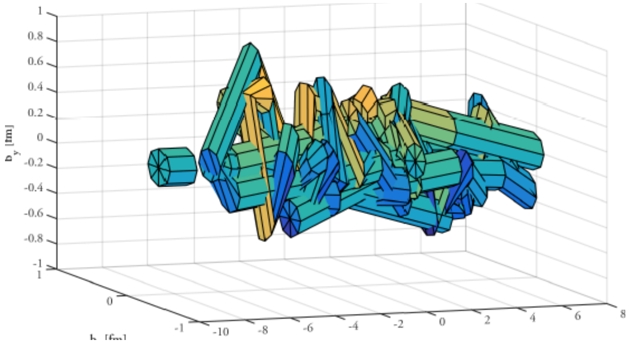
Non-flow $p_T \geq Q_S$ piece of the initial state generate the Glasma graphs – QCD interference "Bose Enhancement" contributions…little jet quenching

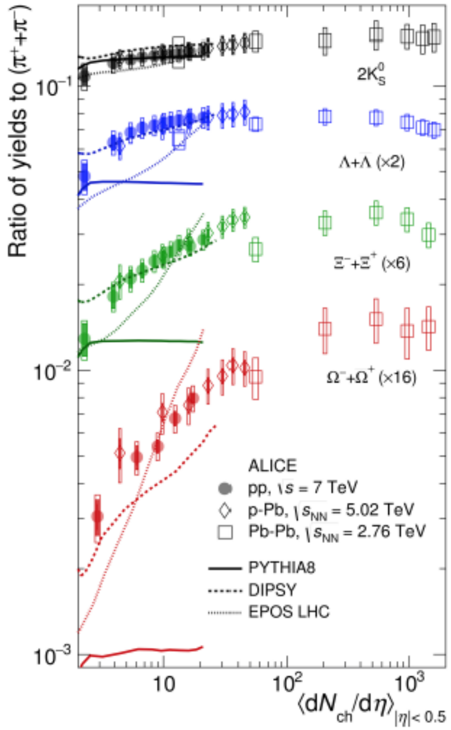
Talks by Altinouk and Kovner

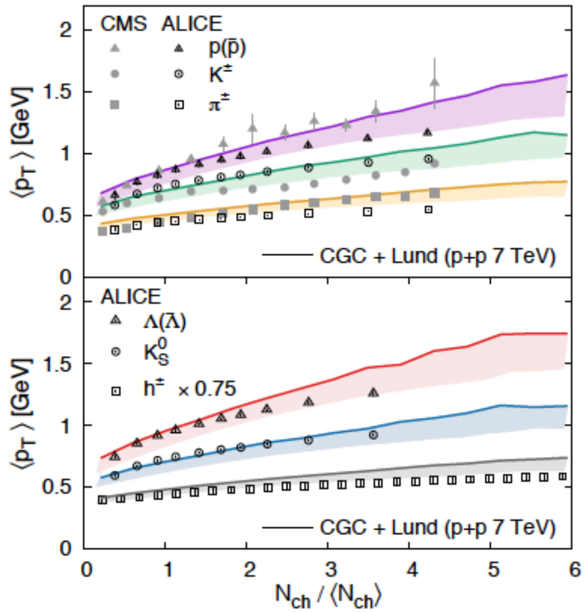
What about this flow+non-flow framework for the smaller systems?

The $p_T < Q_S$ modes flow – described by the Yang-Mills equations – freeze-out before "quasi-particle" rescattering can occur… generate v_2, v_3 and mass ordering…









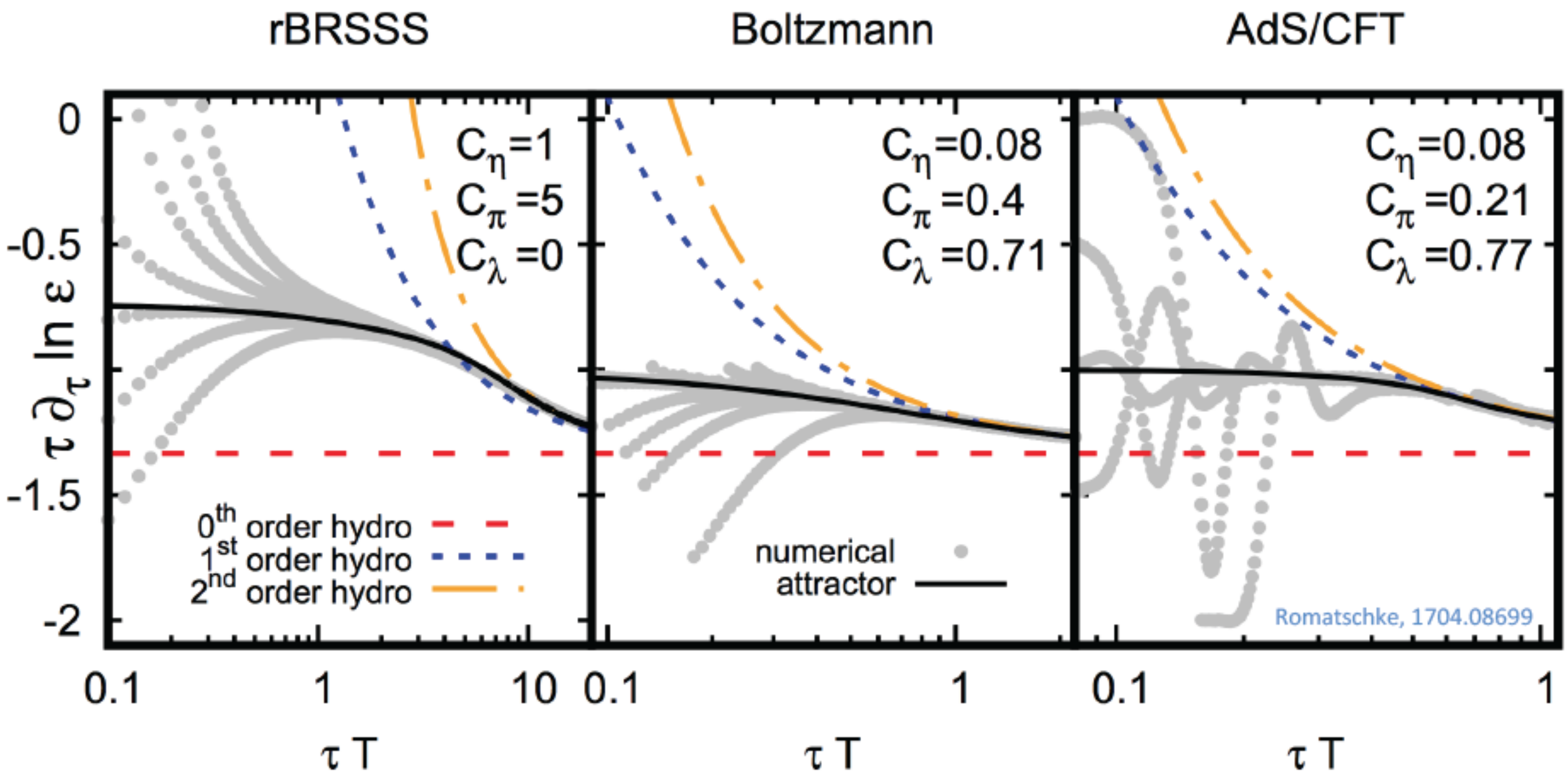
"String shoving" and rope hadronization in DIPSY

Talk by Bierlich

Schenke,Schlichting,Tribedy,RV, PRL117 (2016) 162301

Can one understand this conformal strong field
Yang-Mills flow in small systems within the “hydrodynamization” paradigm?

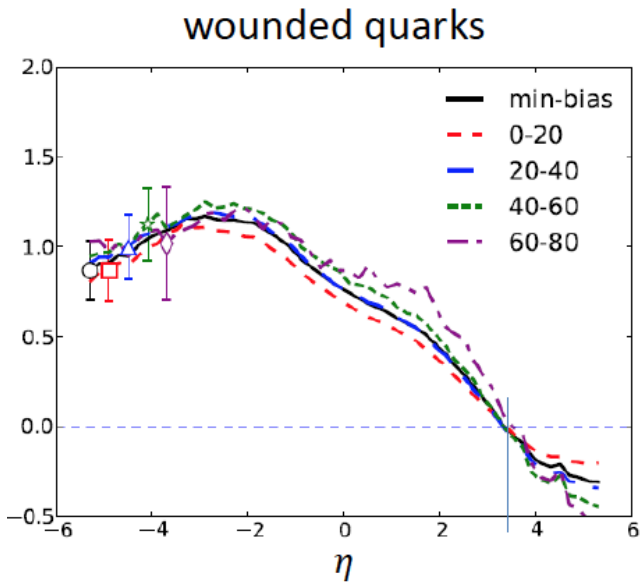
Talks by Romatschke and Spalinski



Simulations of early time dynamics employing holographic ideas

Talks by Attems, Lublinsky, van der Schee

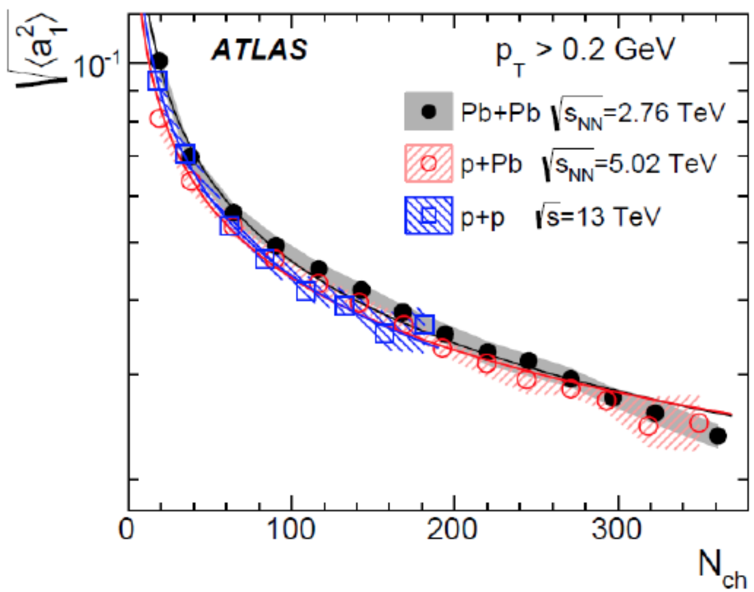
Rapidity correlations and puzzling data on the underlying stringy structure…



Wounded quark model – Can multiparticle production in this framework –developed by the Krakow school -- be related to the CGC?

$$\frac{C_2(y_1, y_2)}{\langle\rho(y_1)\rangle\langle\rho(y_2)\rangle} \sim \langle a_0^2\rangle + \langle a_1^2\rangle \frac{y_1 y_2}{Y^2} + \cdots$$

PRC 95, 064914 (2017)

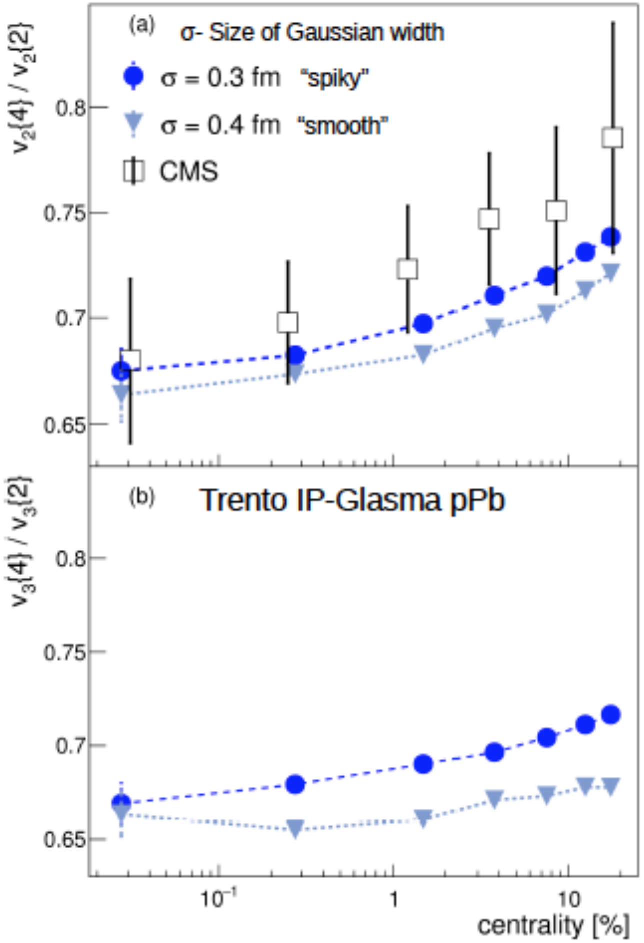


surprising scaling

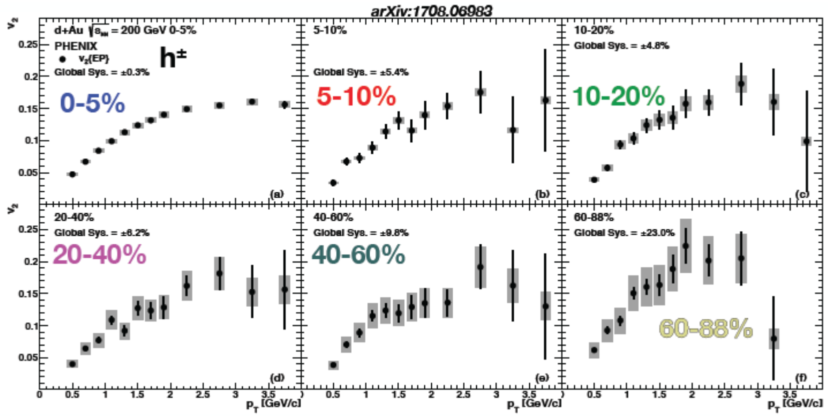
$$\sqrt{\langle a_1^2\rangle} \sim \frac{1}{N_{\rm ch}^{0.5}}$$

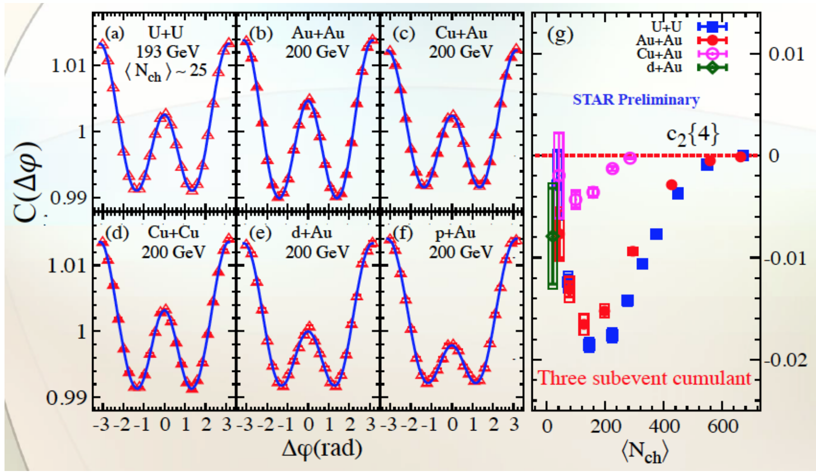
Talk by Bzdak

Going ahead… important benchmarks in the CGC flow/hydro debate



Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.1, 014913

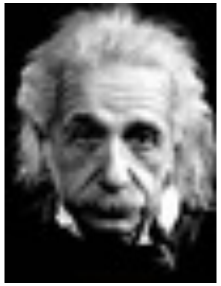




Event engineering & d/3He +Au very important to understand in both frameworks

Theory Talks by Noronha-Hostler,Niemi,Soto-Antoso,Tribedy,…
Experimental talks by McGlinchey,Hill,Nagle,Magdy,Nie,Lacey

Apologies to anyone whose talks I could not cover…but this is not a summary!



"A theory is something nobody believes, except the person who made it. An experiment is something everybody believes, except the person who made it."

Significant advances in both theory and experiment. Keeping this wise remonstrance in mind, we may uncover more remarkable things!

Significant advances in both theory and experiment. Keeping this wise remonstrance in mind, we may uncover more remarkable things!

I am sure I speak for all participants in offering warm thanks to the organizers for a very interesting conference and for their outstanding hospitality in this beautiful city!

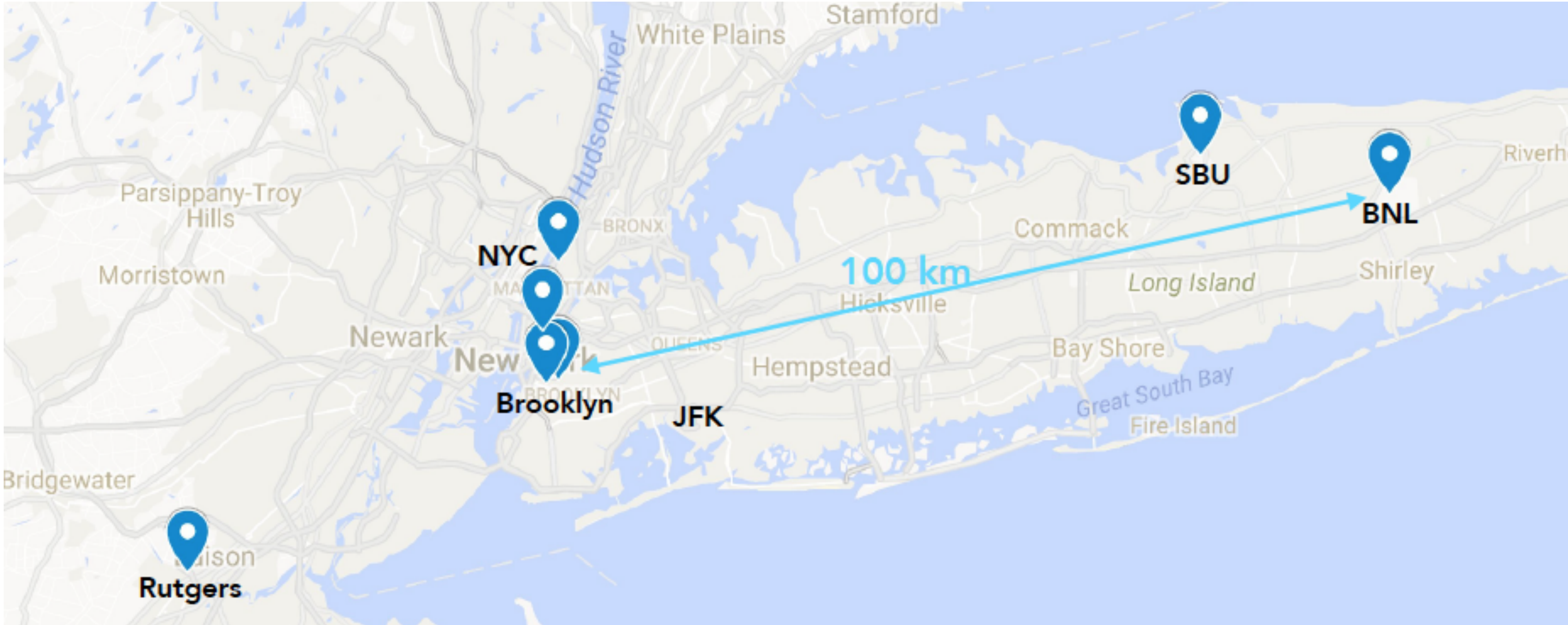
Dziękuję Ci bardzo!!

Announcing... IS2019NY

I ♥ NY®

**Late May or early June 2019,
in the New York City area**

Several locations being considered: *Stony Brook* and *Brooklyn* on Long Island & *Manhattan* (Columbia/CUNY) in NYC and *New Brunswick* (Rutgers) in NJ



Interesting possibilities at each location…we expect a final site selection & fixing of the date soon…

Local organizing committee:

Peter Steinberg & Raju Venugopalan (BNL, co-Chairs)

• Bjoern Schenke • Dave Morrison • Lijuan Ruan • Thomas Ullrich	BNL, theory & experiment
• Agnes Mocsy	Pratt
• Adrian Dumitru • Stefan Bathe	Baruch
• Brian Cole	Columbia
• Derek Teaney • Tom Hemmick • Jiangyong Jia	Stony Brook
• Sevil Salur • Jaki Noronha Hostler	Rutgers
• Helen Caines	Yale
• 2 Temple faculty as JLab representatives	

10 EXPERIMENT
6 THEORY

All the major experiments
are represented on the LOC

Springtime in New York:

We look forward to welcoming you all to the next edition of Initial Stages!